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Stick and slip states in the probe-sample force interaction and informative nanomechanical measurements using AFM

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Most modern atomic force microscopes (AFM) use an optical lever deflection system [1], which may monitor two angles of deflection (bending, torsion) of the console carrying the probe. Alternative methods, as a rule, control one parameter. In the interference and capacitive methods [2] the vertical Z-displacement is measured, the piezoresistive method [3] is the most sensitive to the force F_Z producing the maximum moment. Using any of the mentioned methods is not sufficient to determine the three components of the displacement of the probe or the interaction force [2,4,5]. To completely describe the ideal case without friction, when the probe slides over the surface, it is sufficient to know just one component of the force F_Z or of the displacement Z. In a real situation, the probe may stick or slip at the sample surface, which creates prerequisites for the appearance of ambiguities in the AFM measurements.

In contact and hybrid AFM modes, this leads to the scanning instabilities and to the measurements errors of relief height, interaction forces, contact stiffness, Young's modulus, piezoresponse signals, and also creates limitations for nanomanipulations and nanolithography. In resonance AFM modes, the problem is partly eliminated, but, simultaneously, the possibilities of contact regimes also disappear.

We analyze our recent AFM studies of native, living cells in the hybrid mode (PeakForce QNM): erythrocytes [6], fibroblasts [7], neurons [8,9]. For the comparison, the AFM studies of the artificial objects, partially simulating the living cells, are also presented: micro- and nanoscopic drops of glycerol, Hg and Ga; solid and polymeric test structures with well defined relief. The important features of the PeakForce QNM mode are high speed measurements of indentation force curves and subsequent automatic processing of the detected data array. Due to this, not only the surface relief is studied, but also a whole spectrum of sample's local characteristics: contact stiffness, deformation, probe adhesion to the sample, energy dissipation in the loading-unloading cycle.

The measurement data are analyzed and compared with analytical calculations of the deformations in the console-probe-sample system, taking into account stiffness tensors of the subsystems: cantilever console; a pyramidal probe attached to the edge of the console; sample. (The stiffness tensor describes linear relation between the concentrated force vector and the deformation vector). A general solution is presented for three types of holonomic constraints: the probe sticks to the sample, the probe slides along the selected direction, the probe slides in the selected plane. A particular solution is considered in detail for the case: a rectangular console; "infinitely rigid" probe; a flat sample with finite, anisotropic stiffness, the plane of the sample is deviated from the horizontal by an arbitrary angle.

In particular, the comparison carried out showed the following. With respect to the silicon AFM probe, native fibroblasts behave as slippery (and erythrocytes as sticky) objects, which is manifested by increasing (decreasing) apparent deformation on strongly inclined regions of these cells. The native neurons are sticky with respect to the silicon and nitride silicon material of the probe. This is attributed to the observed decrease in the average apparent Young's modulus with an increase in the ratio of the height of the probe to the length of the console. On flat, horizontal regions of the erythrocytes and neurons, contact stiffness and, as a consequence, the apparent Young's modulus are underestimated. Contact stiffness on flat, horizontal areas of the fibroblasts is measured correctly.

In conclusion, we discuss possible uses of cantilever sensitivity calculations to the displacements of a sample in contact with the probe: improvement of the optical lever deflection

system; accurate AFM measurements accounting for stick-slip effects; optimization of cantilever parameters for effective piezoresponse force microscopy and atomic force acoustic microscopy.

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